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OPTICAL BEAMFORMER

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13. ABSTRACT (Maximum 200 words)

This report describes research on optical beamforming performed in-house at Rome Laboratory. An optically linked antenna array was beamformed using an optical star coupler. Beamforming and nulling was performed using grin lenses as phase elements. The work was performed at an RF of 8 GHz.

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TABLE OF CONTENTS

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LIST OF FIGURES

1.0 Introduction

This report contains the results of work accomplished under Task 3 of in-house project 45194263, entitled "Communications Adaptive Array Processor Evaluation".

As user data rate requiremnts increase, the anti-jamming protection provided by spread spectrum techniques decreases due to bandwidth constraints. Satellite communications systems with data rate/bandwidth shortfalls, using spread spectrum techniques for anti-jam protection are not sufficient to handle projected threats.

The shortfalls in data throughput and anti-jam protection have resulted in renewed interest in adaptive processing technology. In spite of the potential benefits, the progress of integrating adaptive spatial processing (nulling) into communications systems has been very slow. After many years of research and development in adaptive spatial processing algorithms and technology, very few adaptive spatial processing systems have been fielded.

Optically implemented adaptive processing systems have many advantages over digital/analog adaptive processors and could remove some of the size, weight, and power barriers associated with fielding digital/analog onboard MILSATCOM adaptive spatial processing systems. Optical processing techniques could greatly reduce the size, weight, and power required by standard analog/digital adaptive spatial processing communications systems and could eventually provide the means for providing onboard ECCM anti-jamming capabilities.

Adaptive antenna systems normally consist of two or more antenna elements, two or more receivers, amplitude and phase weighting networks for one or more elements and a signal combiner. For some applications the size, weight, power consumption and cost of multiple receivers, antenna elements and associated radio frequency (RF) cabling can be limiting factors. In spite of these limitations, the impressive interference cancellation capabilities of adaptive antenna systems is highly desirable. Recent advances in photonics technology could provide solutions to the limitations described above. RF modulated lasers, optical cabling, optical detectors, summers and phase shifters could reduce much of the size, weight, power consumption and cost of conventional analog/digital adaptive spatial processing systems.

Using the RL/C3 Communications Experimental Facility's anechoic chamber and the "Flexible Adaptive Spatial Signal Processor" (FASSP) this effort was performed to establish the feasibility of using optical technology to implement a four element adaptive spatial processing system using optical components to perform the beamforming and nulling functions. The performance of the optically implemented adaptive spatial processor was evaluated by comparison to a standard analog/digital adaptive spatial processor.

2.0 Adaptive Spatial/Temporal Processor Testbed

RL/C3 has a unique adaptive array processing testbed. The testbed shown in Figure 1 consists of a rectangular anechoic chamber, a flexible adaptive spatial signal processor (FASSP), an antenna pattern recorder, various types of jammer/desired signal sources and satellite communications simulation and analysis programs.

ADAPTIVE ARRAY PROCESSING TESTBED

Figure 1

The testbed simulation/analysis computer programs are used to study and compare adaptive processing system concepts, techniques and algorithms. This provides a "fast-look" approach to determine the merit and feasibility of a concept. If the results show promise the concept is tested further using real signals and adaptive processor hardware to determine the actual benefit attainable. The testbed is reconfigurable and functions as a tool to support the development of methodologies for comparing and evaluating new adaptive spatial processing algorithms, architectures, techniques and devices (including optical), suitable for meeting satellite communications requirements (such as those for the Defense Satellite Communications System [DSCS]).

2.1 Anechoic Chamber

The anechoic test chamber shown in Figure 2 is a rectangular structure 40-foot long, 28-foot wide and 18-foot high [5]. The inner chamber is isolated from RF fields from 150 MHz to 18 GHz by at least 100 dB. It has a six foot diameter spherical quiet zone midway between the ceiling and the floor and about 50 inches from the tips of the absorber on the back wall. The receive element array is positioned in the center of the quite zone to minimize reception of all reflected signals. All chamber walls, ceilings and floors, except walkways, are covered completely with energy (RF) absorbing material. A Scientific Atlanta model 5315C-5 antenna positioner is installed in the chamber. The tip of the model tower (which supports the array elements) is located in the center of the "quiet zone". The chamber is wide enough and has provisions so that several signal sources can be used simultaneously at the back wall opposite to the "quiet zone".

Six feet of the 40-foot chamber is partitioned off and is used as an equipment room to house the signal sources and antenna positioner controls. Absorber panels are removable to allow access for mounting signal/jammer antennas. Signal and control connections between the chamber and the laboratory equipment (FASSP and Scientific Atlanta 2020 system) are provided through bulkhead feed through panels at each end of the chamber.

ANECHOIC CHAMBER

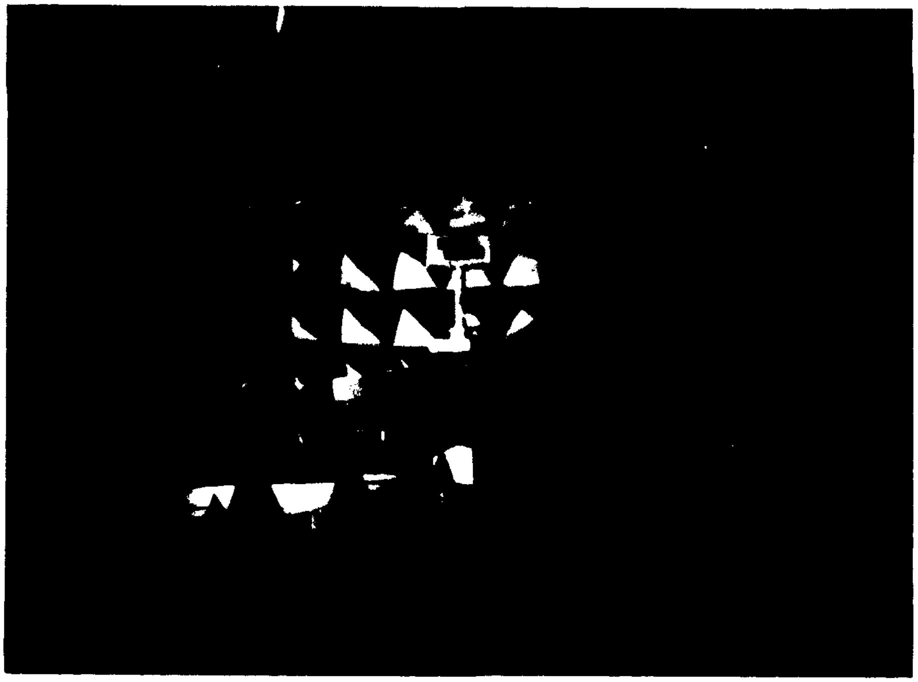

Figure 2

All functions such as source power, frequency, mode and receiver antenna position (pedestal rotation) are controlled from outside the chamber.

2.2 Flexible Adaptive Spatial Signal Processor (FASSP)

The FASSP [4] testbed is shown in Figure 3. All adaptive spatial processing systems consist of three generic components:

1. An array of receiving elements (spatial array) to provide the degrees of freedom required to null out a number of directional jamming signals.

2. An adaptive processor that uses the signal samples from the array receive sensors to compute the adaptive weights that produce the resultant spatial response.

3. Weighting networks that apply the adaptive weights to the signals from the individual input channels.

The design of adaptive spatial processing systems is very complicated because of the close interaction between these three basic components. Although computer simulations can be used to compare the performance of adaptive algorithms and techniques, the hardware implementation effects cannot always be easily modeled.

FLEXIBLE ADAPTIVE SPATIAL SIGNAL PROCESSOR (FASSP)

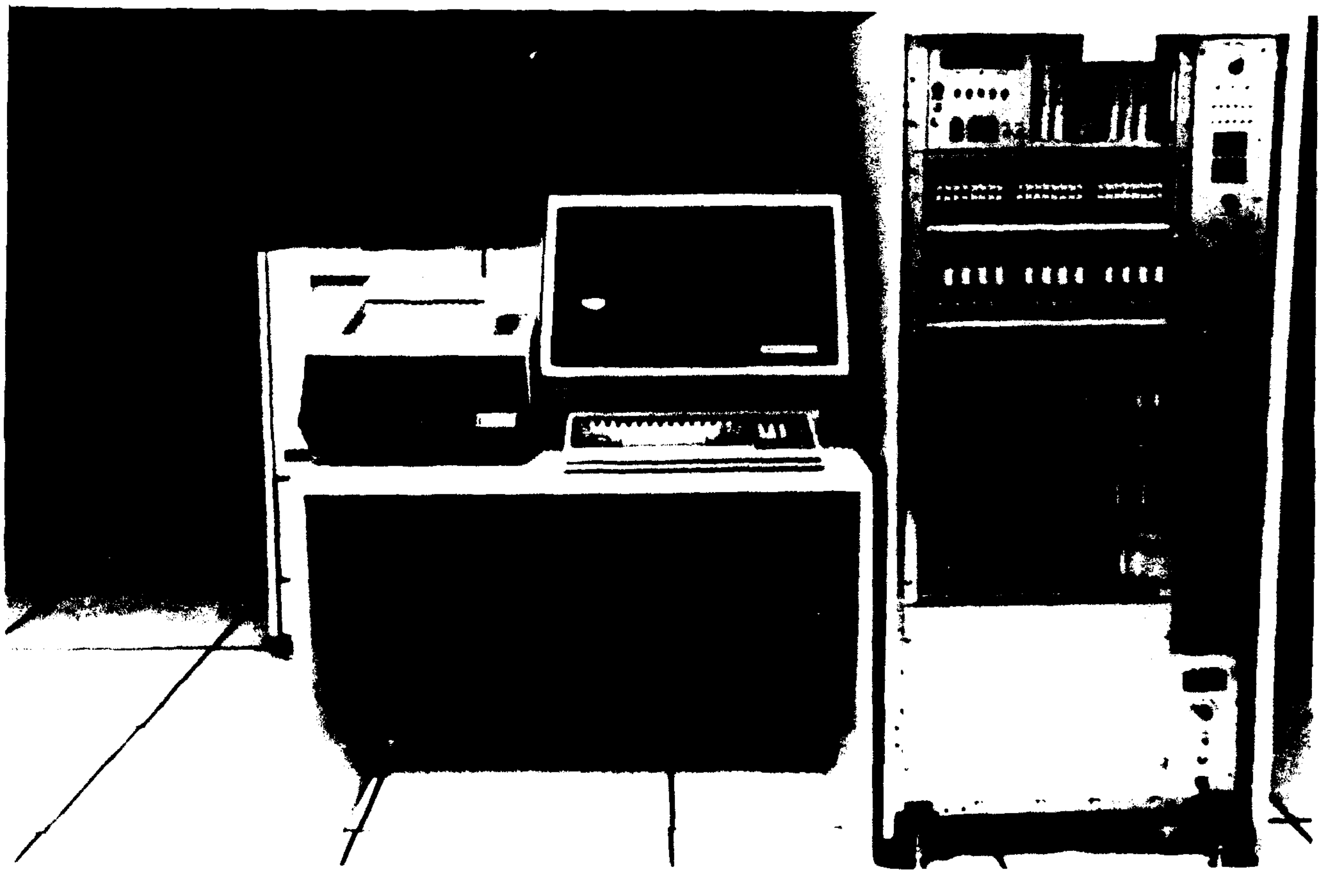

Figure 3

With this in mind, RL/C3BA conceived the ideas of a Flexible Adaptive Spatial Signal Processor (FASSP), which was designed and fabricated for RL by Syracuse Research Corp. The FASSP is a general purpose flexible hardware adaptive array processor system that supports the integration/test of adaptive processing algorithms, architectures, techniques and real components.

The FASSP system was fabricated with high performance quality components and consists of 12 real RF receivers and weighting networks that are reconfigurable. The designer uses a computer-based operating system to select the adaptive algorithms and hardware configuration and specify the necessary adaptive processor system parameters. The adaptive processor system performance can then be evaluated using real RF desired and jamming signals.

3.0 Conventional Adaptive Array Baseline

The conventional adaptive array processing system shown in Figure 4 was used as the baseline system configuration. The receiver antenna was a line array of four standard gain horns separated by 3/2 wavelength spacing. The array was located on the positioner with the elements centered in the chamber quiet zone. The optically linked adaptive array configuration is shown in Figure 5 and is described in Section 4.

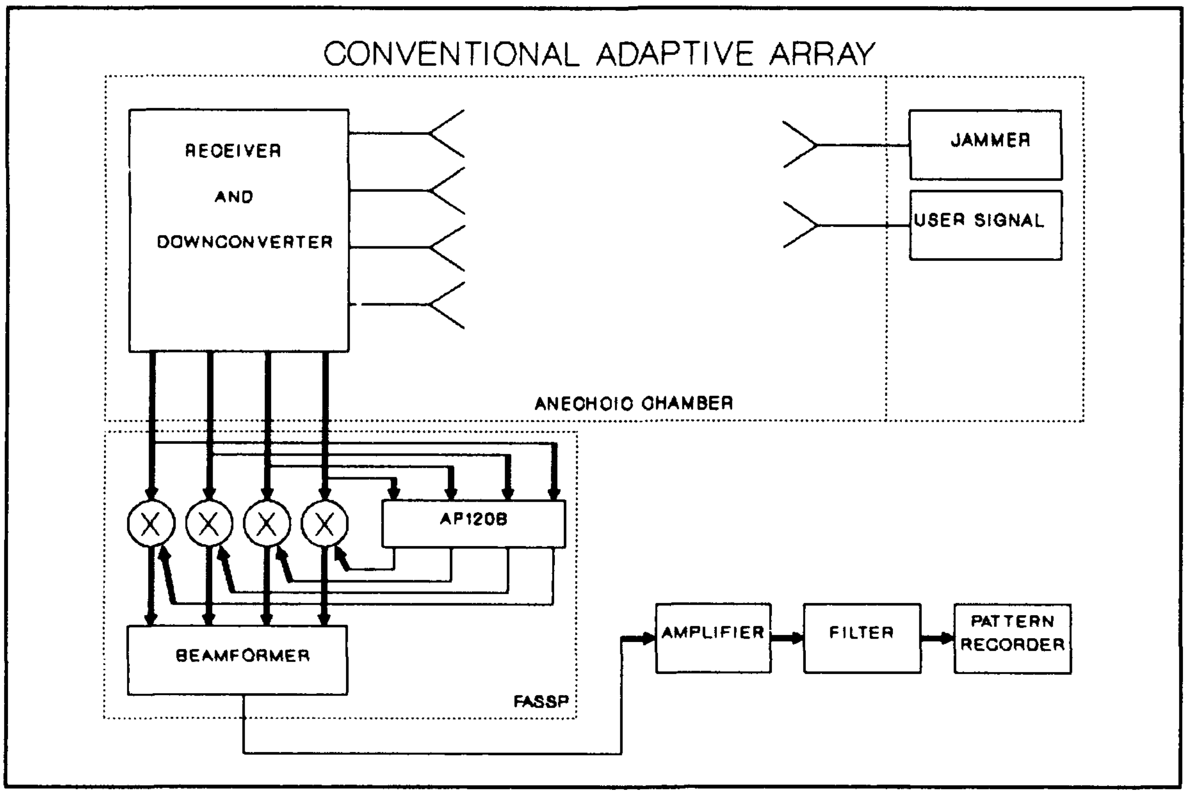

Figure 4

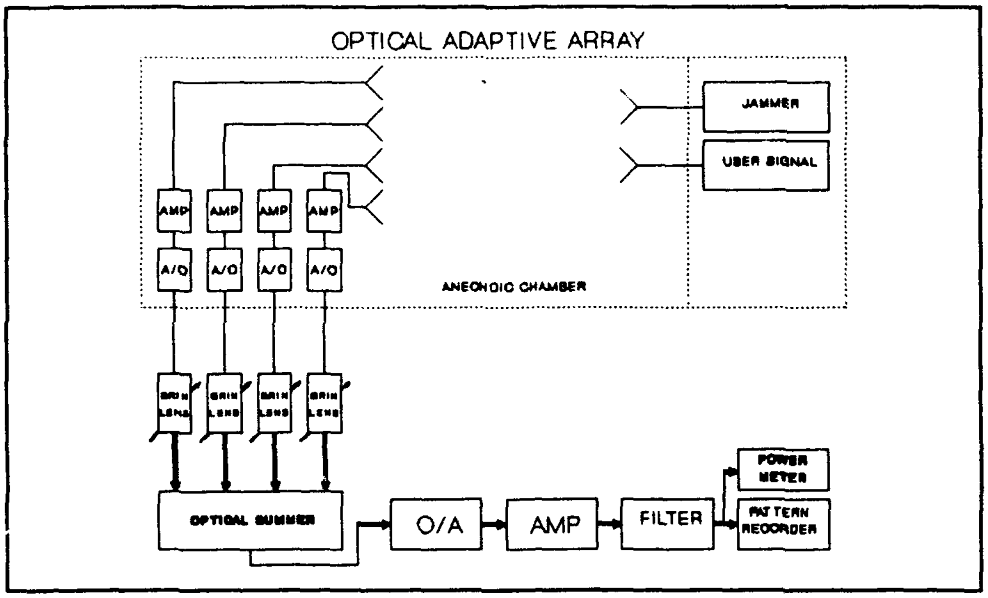

Figure 5

The CW and wide band noise jammer antennas were located at the opposite end of the chamber. One jammer transmitter element was positioned broadside/boresight (zero degrees azimuth, zero degrees elevation) to the array and a CW signal was applied. Figure 6 is a plot of the array steered to that CW source.

BEAMFORMED ARRAY PATTERN

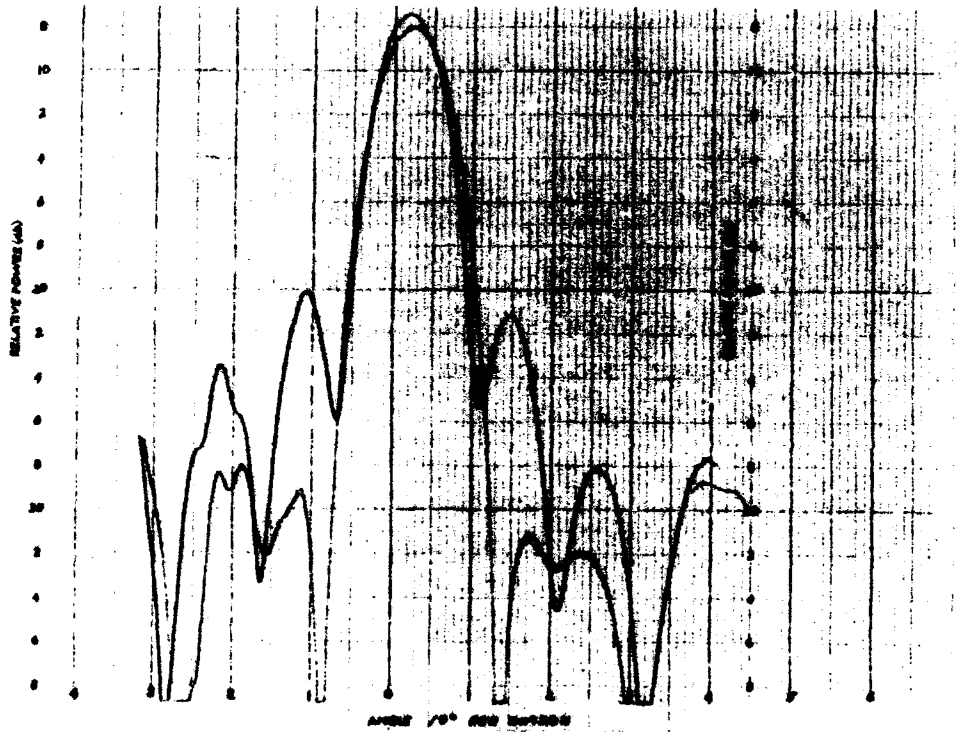

Figure 6

The array response plot shows that the main beam is centered at zero degrees azimuth and the sidelobes are located at plus or minus fourteen degrees azimuth. The second jammer transmit element was positioned at fourteen degrees centered on one of the side lobes.

Nulling and beamforming functions were then performed using desired and jamming RF signals at each position.

3.1 Baseline Performance Measure

Cancellation ratio (CR) was the performance measure used to compare the performance of the optical implementation with that of the standard coaxial implementation.

CRs for a given input jamming signal are measured by comparing the adaptive and conventional output power of the adaptive processor. Usually, CR is used to characterize the performance of the adaptive processor against different jamming scenarios. It is a direct measure of the adaptive processor nulling capability and is shown in Equation 1 where Pa is the adaptive processor output power in the adaptive mode and Pc is the adaptive processor output power in the conventional or beamformed mode.

$$CR(dbm) = 10\log(Pa/Pc) \qquad 1$$

Normally adaptive processor output is measured in dbm and thus Equation 2 is used to compute the CR ratio.

$$CR(dbm) = Pa(dbm) - Pc(dbm) \qquad 2$$

4.0 The Optically Implemented Adaptive Spatial Processor

A basic adaptive spatial processor system consists of an array of spatially separated antenna elements, individual receiver RF channels for each antenna element, weighting networks (multipliers), adaptive weights and a beamformer (summer) output network. One channel of such a system is shown in Figure 7. The block marked "Flexible Adaptive Spatial Signal Processor" (FASSP) indicates the equipment that performs the adaptive signal processing tasks. Because of the losses in the RF cabling, the SHF receivers are co-located with the antenna elements in the anechoic chamber. Along with the RF/IF cabling, the receivers introduce another source of unwanted RF/IF radiation and reflections.

The results of in-house work related to removing the RF/IF coaxial cables and receivers from the anechoic chamber and replacing the cables with optical links is documented in RL-TR-90-183, entitled, "Optically Linked SHF Antenna Array", Jul 90. The very low losses in the optical fiber make it possible to remove the SHF receivers from the chamber and co-locate them with the FASSP. The optical linkage also eliminates the RF/IF coaxial cables from the chamber.

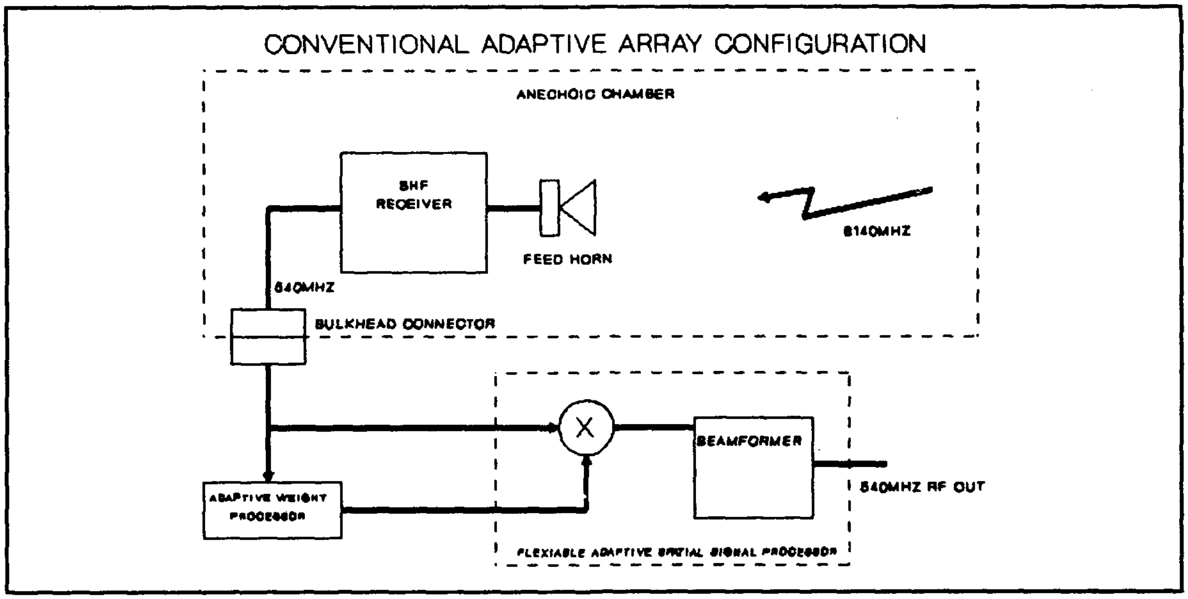

Figure 7

Shown in figure 8 is one channel of an optically linked adaptive spatial processor.

OPTICAL ADAPTIVE ARRAY

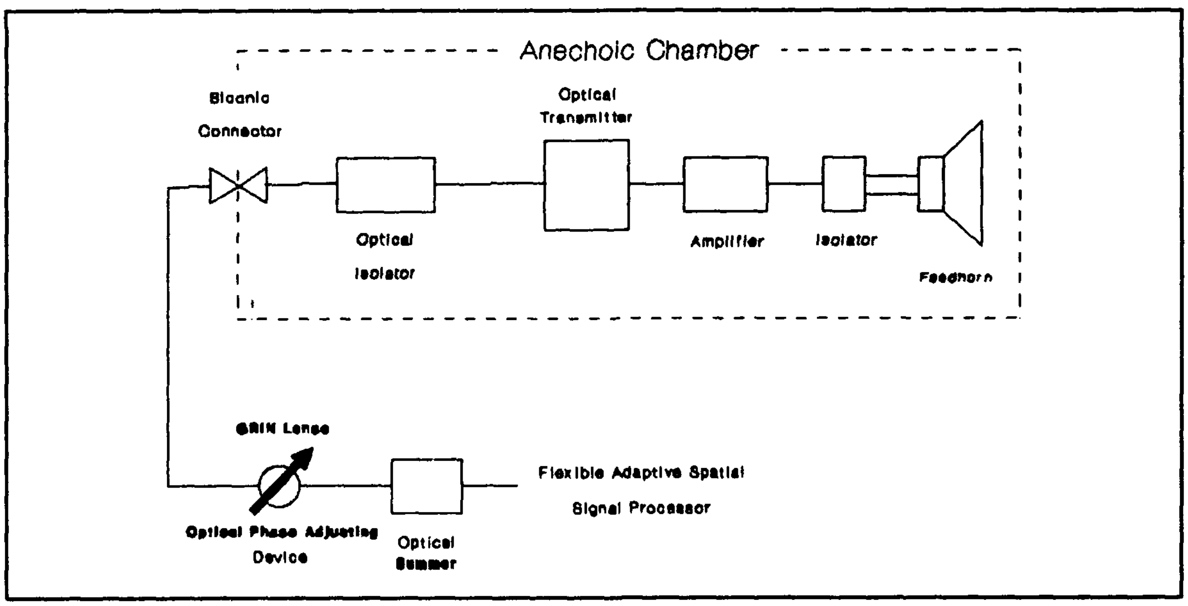

Figure 8

4.1 Hardware Description

Component selection was based on the anechoic chamber and associated equipment interface requirements. Since the FASSP system was designed to operate at 8140 GHz, the task of optical link, weighting network and beamformer was greatly simplified. Ortel TSL-1000 optical transmitters and Ortel RSL-25 optical receivers were selected based on their frequency compatibility.

Since the maximum received signal likely to be seen at the output of each antenna element (feedhorn) is less than -40dBm, 50dB gain narrowband (centered at 8 GHz) amplifiers were required. This will supply the Ortel transmitters with power levels near their maximum RF input level of 12 dBm thereby allowing maximum dynamic range usage of the optical links.

Other devices incorporated in each channel of the adaptive spatial processor were electrical and optical isolators to compensate for impedance mismatch reflections from the feedhorns and optical reflections to the laser. 50 meter lengths of fiber optic cable, time adjusting weighting networks and a star coupler optical summing device were also integral parts of the optical adaptive spatial processor.

4.2 Functional Description

Each channel of the adaptive spatial processor consists of the equipment described in section 4.1. An adaptive spatial processor is comprised of two or more channels, usually one for each antenna element in the array. Each channel of the optical adaptive spatial processor is identical. In terms of a single link, the RF signal arrives at the array and is captured by the antenna elements, in this case SHF standard gain horns. The RF isolators remove the effects or impedance mismatch between the SHF horns and the low noise figure, high gain amplifiers. (The low level RF signals are then amplified to provide the appropriate signal level to the optical transmitters, which directly amplitude modulates the laser to produce a single frequency of light.) The light is then transmitted through the optical fiber to the grin lens where the optical signal is weighted in time and phase. Optical weighting is accomplished by varying the optical path length through the grin lens.

Next, the weighted optical signal outputs of each channel are combined (summed) at the star coupler output. This optical beamformer or adaptive spatial processor residue signals then converted to a standard analog signal by optical detectors.

5. Test and Evaluation

The optically implemented adaptive spatial processor design described in section 4 had significant design flaws which prevented the nulling/beamforming functions from being performed. Details of the lessons learned and recommendations are contained in section 6. For completeness of this report, the results of the baseline analog/digital adaptive spatial processor will be presented.

Data was collected to plot cancellation ratios for three separate scenarios. All of the figures indicated below are identical in form. The horizontal axis (Pe) is the ratio of signal plus noise to noise power as measured at the antenna element. On the vertical axis, two quantities are plotted. The quantity (Pc) is referred to as the conventional or unadapted output power as measured at the beamformer/residue output port of the adaptive processor. When measuring this signal power, the array is beamformed (or steered to broadside). Then the interference/jammer signal is activated and the signal plus noise ratio is measured. The quantity (Pa) is referred to as adaptive spatial processor residue power after the processor is adapted to the steady state solution. Again the signal plus noise to noise ratio is measured at the residue output. Using these graphs, the cancellation ratio (in dB) can be read directly as the difference between the two plotted lines on the graph.

Shown in Figure 9, 10, and 11 are plots of the baseline analog/digital adaptive spatial processor, conventional and adapted steady state response. The signal scenarios for each plot are as follows:

Figure 9 - CW Signal in Array Mainlobe
Figure 10 - CW Signal in Array Sidelobe
Figure 11 - Wideband Noise Signal in Array Mainlobe

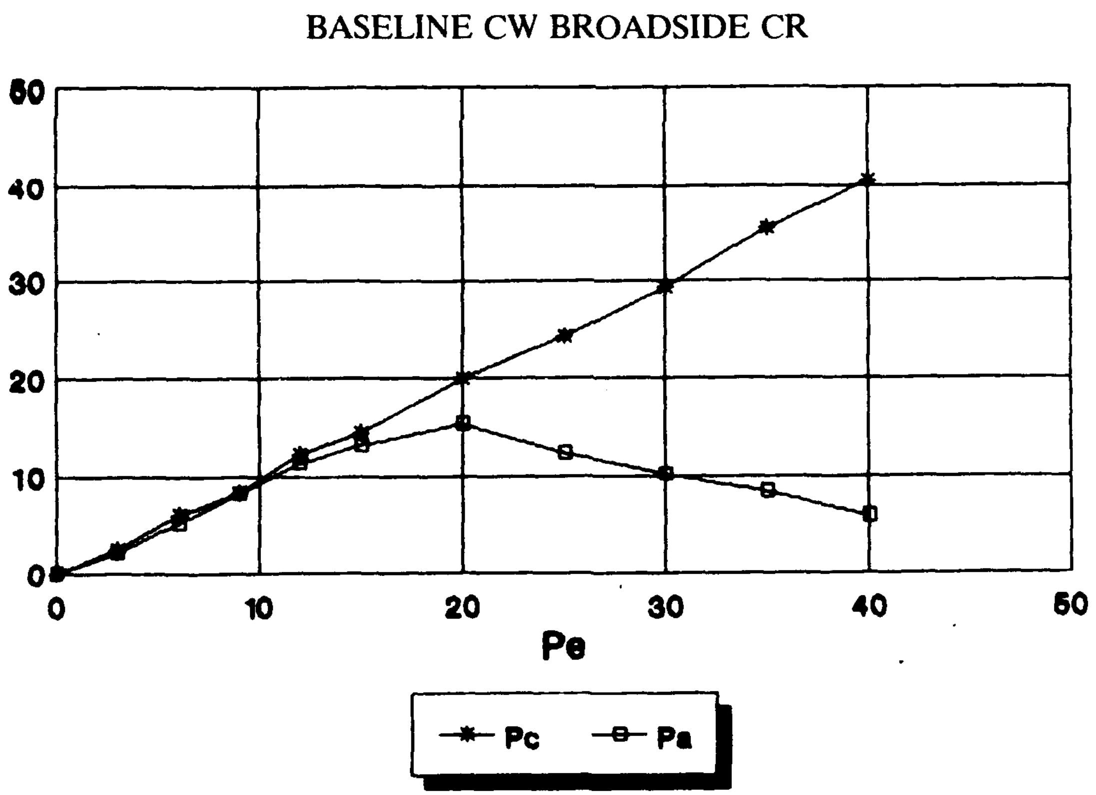

Figure 9

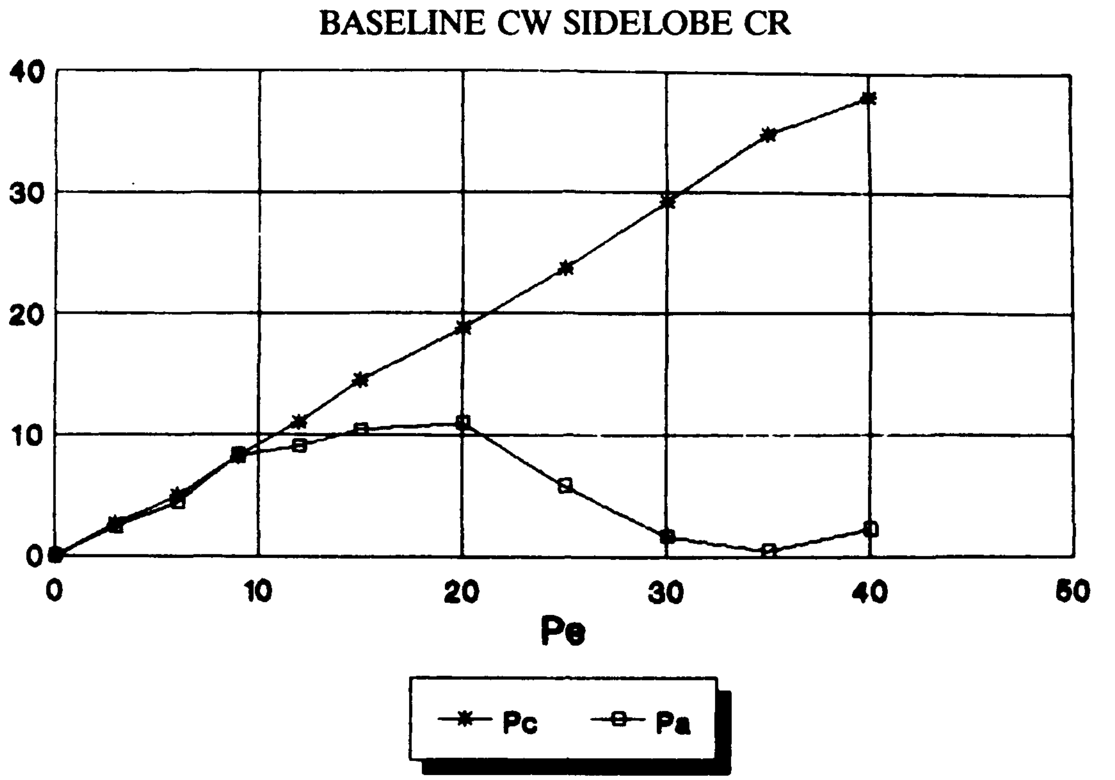

Figure 10

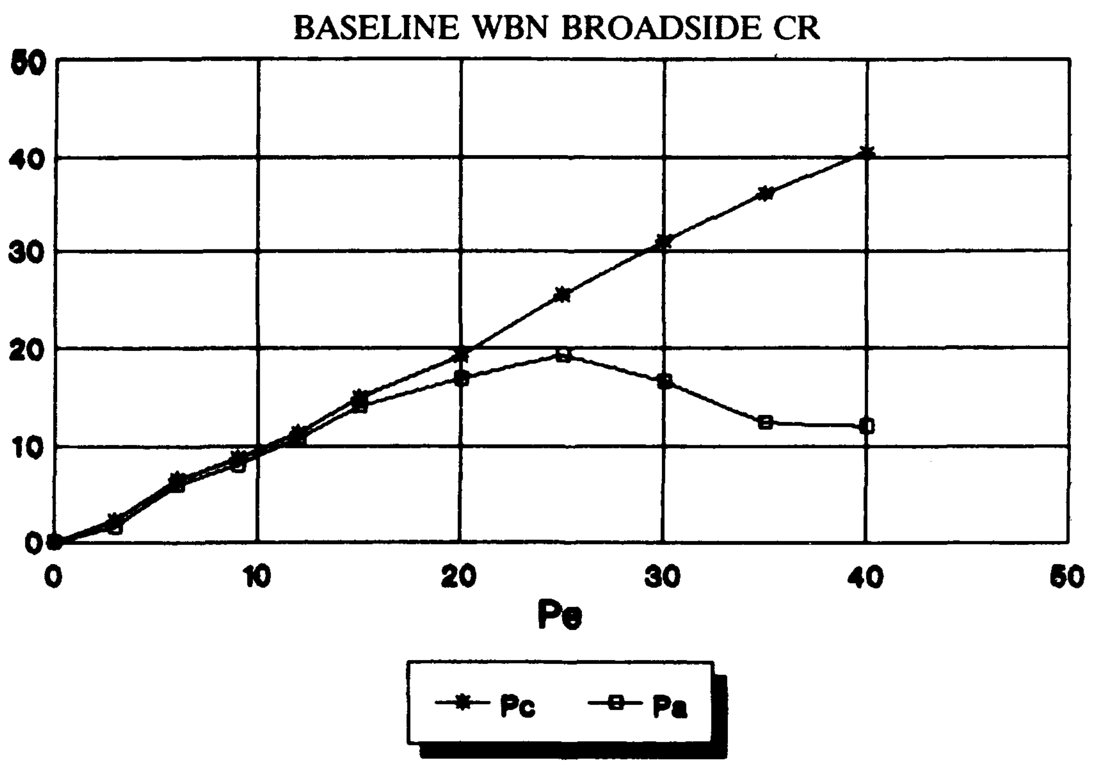

Figure 11

Since beamforming and nulling functions could not be performed with the optical processor, performance comparisons between the baseline analog/digital and optical adaptive spatial processor were not accomplished.

6.0 Conclusions and Recommendations

Post analysis of the optically implemented processor has indicated that individual, directly modulated optical transmitters (laser) can not be used to perform the necessary nulling/beamforming functions. In order to weight and sum light energy from independent channels, the light energy in each channel must be coherent. Since externally modulated lasers are now available from vendors, an optical adaptive spatial processor design such as the one shown in Figure 12, could be fabricated, tested, and evaluated. The light energy from a single laser would be divided equally among the four individual channels, modulated, weighted, and summed. This configuration would ensure optical coherence and make this adaptive processor design even more cost effective than the implementation tested.

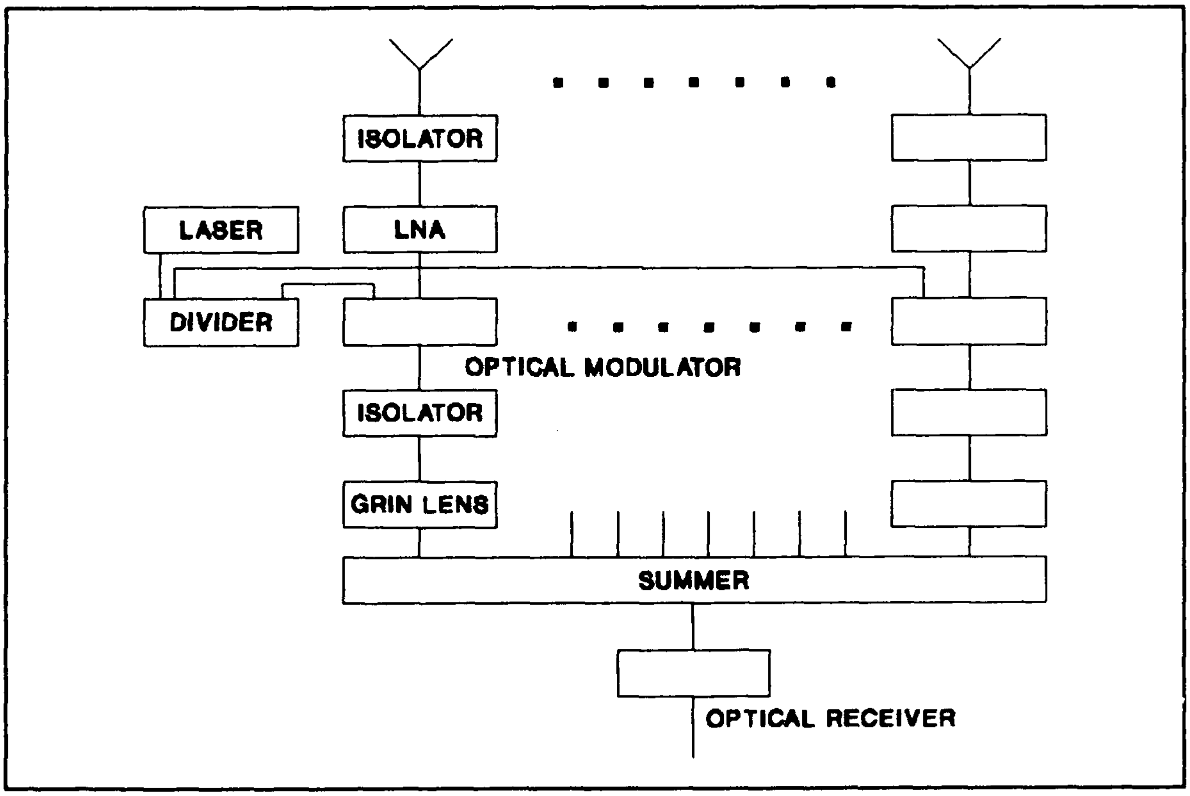

Figure 12

Externally modulated lasers have more dynamic range that directly modulated lasers. Their use will also increase the adaptive processor dynamic range. Single mode fiber optic cable should be used instead of multimode cable. This would prevent cable losses due to gradient effects when the fiber is bent or deformed in any way. These means of improvement will be further investigated and verified in future in-house efforts. This

RL/C3BA in-house investigation of optical technology, as applied to adaptive antenna systems, indicates that evolving optical technology can and will provide important enhancements especially for onboard SATCOM systems.

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